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Memory retrieval as temporal discrimination ☆

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ABSTRACT

Temporal distinctiveness models of memory retrieval claim that memories are organised partly in terms of their positions along a temporal dimension, and suggest that memory retrieval involves temporal discrimination. According to such models the retrievability of memories should be related to the discriminability of their temporal distances at the time of retrieval. This prediction is tested directly in three pairs of experiments that examine (a) memory retrieval and (b) identification of temporal durations that correspond to the temporal distances of the memories. Qualitative similarities between memory retrieval and temporal discrimination are found in probed serial recall (Experiments 1 and 2), immediate and delayed free recall (Experiments 3 and 4) and probed serial recall of grouped lists (Experiments 5 and 6). The results are interpreted as consistent with the suggestion that memory retrieval is indeed akin to temporal discrimination.

This paper examines the claim, made by recent temporal distinctiveness models of memory, that retrieval from memory often involves temporal discrimination. Our focus is specifically on the role of time, and temporal discrimination, in serial and free recall. Several time-based models of memory for serial order have been developed in recent years. These have been applied to serial order memory over relatively short time periods (Brown, Neath, & Chater, 2007; Brown, Preece, & Hulme, 2000; Burgess, 1995; Burgess & Hitch, 1992; Burgess & Hitch, 1996; Burgess & Hitch, 1999; Glasspool, 1995; Gupta, 1996; Hartley & Houghton, 1996; Henson, 1998; Henson & Burgess, 1998; Hitch, Burgess, Towse, & Culpin, 1996; Houghton, 1990; Houghton, 1994); memory over longer timescales (Brown, Della Sala, Foster, & Vousden, 2007; Brown, Neath, et al., 2007; Brown et al., 2000; Neath & Brown, 2006), and speech production (Hartley & Houghton, 1996; Houghton, 1990; Vousden, Brown, & Harley, 2000). These models differ from one another in many ways, but several have in common the assumption that items' sequential relations are encoded via the association of items to successive states of a time-varying learning-context signal of some kind. Such models, with temporal mechanisms at their heart, have proved successful at accounting for a wide range of empirical data from the study of short-term serial recall. However temporal-context models have not generally been related to temporal processing outside the context of memory retrieval, nor have they been generally applied outside serial memory and speech production paradigms (although see Howard & Kahana, 2002, for a temporal-context model of free recall).

Here therefore we focus on a particular class of time-based models: *temporal distinctiveness* models (e.g. Baddeley, 1976; Baddeley & Hitch, 1977; Brown, Della Sala, et al., 2007; Brown, Neath, et al., 2007; Crowder, 1976; Glenberg & Swanson, 1986; Lewandowsky, Duncan, & Brown, 2004; Neath, 1993a; Neath, 1993b). Such models are typically more abstract than the temporal-context models described above, have seen wider application to free recall, and (as we shall see below) in some cases make clear

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predictions about the relation between temporal discrimination and memory retrieval. Temporal distinctiveness models are typically motivated by the analogy of a line of telegraph poles receding into the temporal distance (cf. Bjork & Whitten, 1974; Crowder, 1976) or items moving past an observer along a conveyor belt (Murdock, 1974). For example, consider Fig. 1a, which depicts a line of telegraph poles as they appear receding into the past from the point of view of a stationary observer (cf. Crowder, 1976). Spatially closer poles are more easily discriminable from one another than are more distant poles—the poles close to the observer are more spatially distinctive. A key tenet of temporal distinctiveness theories is that memory is affected by items' distinctiveness along a temporal dimension, just as ease of recall may be affected by semantic or spatial distinctiveness. Some temporal distinctiveness theorists argue that remembering is analogous to perception, in the sense that it involves discriminating between items in a set of memory representations, and that this discrimination is affected by the distinctiveness of item representations. However, all make the prediction that more temporally distinctive representations in memory will, other things being equal, be associated with superior memory performance. These models have generally (although not exclusively) been applied to rather different phenomena than have the temporal-context models, focusing in particular on long-term recency effects and the "ratio-rule" (Baddeley, 1976; Bjork & Whitten, 1974; Glenberg, Bradley, Kraus, & Renzaglia, 1983; Tan & Ward, 2000). Neath and Brown (2007) review and discuss the relation between different notions of distinctiveness.

A recent implemented temporal distinctiveness model, SIMPLE (Brown, Della Sala, et al., 2007; Brown, Neath, et al., 2007; Neath & Brown, 2006) instantiates the telegraph pole analogy. Following exemplar models (e.g. Nosofsky, 1986) SIMPLE assumes that items in memory can be seen as occupying locations in a multidimensional memory space. According to SIMPLE, an important dimension in this multidimensional space represents the (logarithmically transformed) temporal distances of items at the time of retrieval. The idea is illustrated in Fig. 1b and c (where only the temporal dimension is illustrated, although others are assumed to be important: see Brown et al. for detailed discussion and implementational details). Fig. 1b shows the actual (untransformed) temporal distance of items from a five item list, where the items are presented at the rate of one item every 2 s and recall takes place 1 s after the offset of the final list item. Fig. 1c shows the same distances after compression, such that more temporally distant items occupy less isolated/distinctive locations along the temporal distance dimension. According to SIMPLE, Fig. 1c represents memory locations for a list of unrelated items along the temporal dimension. Brown et al. suggested that recall of items from memory in terms of their location along a temporal dimension is a kind of discrimination problem. Moreover, the required discrimination is equivalent to that required during the identification of stimuli in terms of their position along any other dimension such as weight, line length, or loudness.

Items in memory will be difficult to retrieve to the extent that they occupy crowded regions along the temporal distance dimension in memory. Thus, SIMPLE offers an instantiation of the telegraph pole analogy. Recent items will be advantaged because they occupy more isolated (and hence distinctive) locations along the temporal distance dimension; the first few items in a list will also receive some advantage because they have competing neighbors only on one side (i.e., primacy items can benefit from 'edge effects').

A key signature of a temporal distinctiveness model such as SIMPLE is therefore an asymmetric serial position curve, with substantial recency (for items tested immedi-

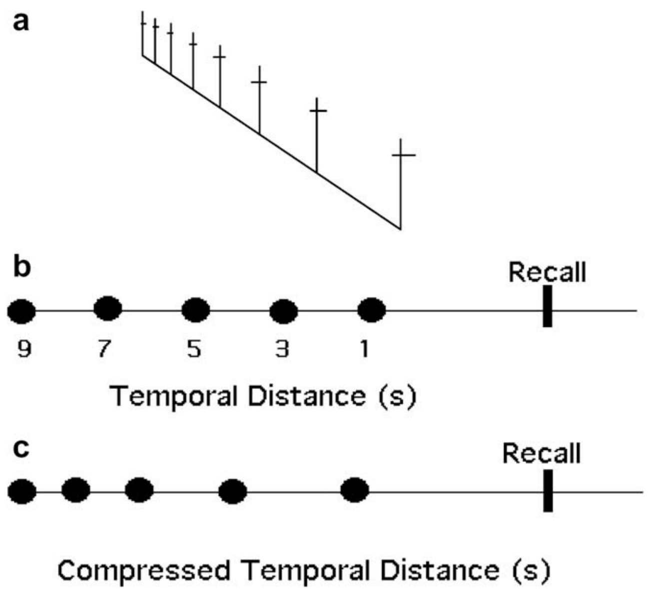

Fig. 1. Illustration of the telegraph pole analogy of memory.

ately after list presentation is completed) and smaller primacy. The prediction of a primacy effect, even in the absence of any rehearsal processes, distinguishes such models from "ratio-rule" models (e.g. Tan & Ward, 2000) which, absent rehearsal, predict only a recency gradient with no primacy effect. The prediction of recency when testing is immediate also distinguishes the predictions of models such as SIMPLE from purely positional models, which do not naturally predict large and extended recency.

The model has been applied to a wide range of phenomena in free and serial recall (Brown, Della Sala, et al., 2007; Brown, Neath, et al., 2007; Lewandowsky et al., 2004; Neath & Brown, 2006; Neath & Brown, 2007); here we focus on more general predictions of temporal distinctiveness models. From most memory tasks there is already evidence that memories are temporally organised. Items that are more temporally isolated from their immediate list neighbors at presentation, and which could therefore be expected to occupy more isolated and hence more discriminable locations along the temporal distance dimension, are indeed better recalled in free recall (Brown, Morin, & Lewandowsky, 2006) and better recognized (Morin, Brown, & Lewandowsky, unpublished). Temporally isolated items are also better recalled in serial order memory tasks when recall order is unconstrained (Lewandowsky, Nimmo, & Brown, 2008), and in running memory span (Geiger & Lewandowsky, 2008) although the effect is absent or at least smaller in conventional forward serial recall tasks (e.g. Lewandowsky & Brown, 2005; Lewandowsky, Brown, Wright, & Nimmo, 2006; Lewandowsky, Wright, & Brown, 2007; Nimmo & Lewandowsky, 2005; Nimmo & Lewandowsky, 2006; Parmentier, King, & Dennis, 2006). The presence of clear temporal isolation effects in a range of memory tasks appears consistent with temporal distinctiveness models of memory. Forward serial recall may represent an exception, perhaps because it is the only task which is "ballistic" in the sense that retrieval, once initiated, may proceed relatively automatically and without strategic intervention (Lewandowsky, Brown, & Thomas, in press). For this reason we do not use forward serial recall tasks in the present paper.

The focus of the present paper is on a second, and strong, prediction from temporal distinctiveness models such as SIMPLE. According to such models, an important component of retrieval is akin to discrimination of temporal durations (where the temporal durations correspond to the temporal distances of items at the time of retrieval). The locations of items along the temporal distance dimension (which are confusable for temporally distant items, and less confusable for temporally recent items) are simply the logarithmically transformed temporal durations. Thus the confusability of the temporal durations from one another, in a task that simply involves identification of temporal durations (e.g. short and long tones) should correspond to the discriminability of items from one another in a memory task.

For example, consider a probed serial recall task of a list of seven items presented visually at a rate of one per second. If memory for each item is tested 1 s after presentation finishes, via a positional probe, then the temporal distance of the various items in memory at the time they must be retrieved are 1, 2, 3, ..., 6, 7 s. When items are highly familiar, the discriminability of the memory location of (say) item 3, which occurred 5 s before the time of retrieval, should be similar to the discriminability of a temporal duration of 5 s in the context of other temporal durations of 1 s through 7 s in a task involving absolute identification of temporal durations.

Of course, memory items are represented in terms of a multidimensional psychological space, not only along a temporal dimension. Therefore, confusability of items along additional (non-temporal) dimensions should also influence the retrievability of items from memory. In examining the free or serial recall of unrelated words or letters, however, such factors can be expected to do no more than add noise, acting against the hypothesis under test.

The plan of the rest of the paper is as follows. Our general strategy is to look for similarities between (on one hand) the probability of recalling memories as a function of their temporal distances, and (on the other hand) the ease of identifying the same temporal durations in a separate study that examines identification and discrimination of temporal durations directly. We used an absolute identification task to examine temporal processing. In an absolute identification task, items are identified from one another in terms of their position along a dimension (weight, loudness, brightness, temporal duration, etc.). When absolute identification of temporal durations is required (Brown, McCormack, Smith, & Stewart, 2005; Lacouture, Grondin, & Mori, 2001), participants initially hear a set of tones differing from one another only in temporal duration. A label is associated with each stimulus. In the experiments we describe below, the labels are always numbers (e.g. 1 through 9), with the number for each item corresponding to the item's ordinal position on the continuum of temporal duration (e.g. 1 for the shortest tone; 9 for the longest). Subsequently, in the main part of the experiment, participants hear individual stimuli in random order and are required to identify them with the correct label. Feedback regarding the correct response is given after each trial.

The first two experiments examine probed serial recall of short lists (Experiment 1; see e.g. Woodward, 1970) and the absolute identification of temporal durations (Experiment 2) where the durations in Experiment 2 correspond to the temporal distances of items in Experiment 1. Experiments 3 and 4 follow the same logic for immediate and delayed free recall, while the final two experiments look at serial recall of grouped lists (Experiment 5) and identification of the corresponding temporal durations (Experiment 6). The overall hypothesis in all cases is the same: The items that are most likely to be recalled in a memory task are those items whose temporal distances (at the time of retrieval) are least confusable with the temporal distances of other items.

Experiment 1

In this experiment performance using the probed recall memory paradigm was examined. Participants were required to attend to a list of visually presented letters, and to recall the position of one of the letters when probed with that letter at the end of the presented list. An important aspect of this procedure is that the retention interval (measured from list end to recall probe) is the same for every item. Thus the temporal distance of each item (the time from the offset of an item's presentation to the time it must be recalled) is known, in a way that is less straightforward to achieve with forward serial recall tasks or free recall tasks. A rapid rate of presentation was used to prevent rehearsal.

Methods

Participants

Sixteen undergraduate students from the University of Warwick (mean age 23 years) acted as participants. Each received payment of £5 for taking part.

Materials

The experiment was run on computer and presentation of the stimuli was controlled by purpose written software. The stimuli were seven non-confusable letters: M H Z R J Q Y. The letters were presented visually on the computer screen, one at a time. Each list consisted of seven letters, and was constructed by randomly shuffling the seven stimuli on each trial. Participants were presented with a total of 266 lists. The probe was displayed after list presentation on the computer screen by showing one of the items in the list alongside a question mark. Visual feedback was provided throughout the task on the visual display of the computer as the correct position of the probe stimulus.

Procedure

During each session, participants completed the probed recall task, plus an absolute identification of duration task, reported here as Experiment 2. Half the participants completed the probed recall task followed by the absolute identification of duration task and half the participants completed the tasks in reverse order.

Participants completed the experiment sitting in a quiet room at a comfortable distance from the computer. Participants were told that they would see a list of seven letters, appearing one at a time, on the computer screen, and that they should read each letter aloud as it appeared on the screen. At the beginning of each trial, the word "ready" appeared in the middle of the screen for 900 ms to prepare participants for the trial. After the "ready" prompt, the screen was blank for 700 ms before the trial began. Each letter appeared in the middle of the screen for 333 ms. Three hundred and thirty-three milliseconds after the last letter had been presented, the probe letter, alongside a question mark, appeared in the middle of the computer screen. This was the cue for participants to recall the presented position of the probe item. Participants were instructed to respond as soon as they could, by pressing specially labelled keys on the keyboard, corresponding to each serial position in the list. Responses were recorded and timed by the computer. The probe item stayed on the screen until participants had made their response. Immediately following their response, the feedback display "That was position X" appeared in the middle of the computer screen for 1100 ms. After 42 trials there was an opportunity to take a short break and then the experiment continued. Participants completed a total of 266 trials before the task was complete. At the end of the task, each serial position had been probed 38 times.

Results

The first 14 trials familiarized participants with the procedure and were not included in the analysis, leaving a total of 36 probes per position for analysis. For each list, responses were recorded as a function of the serial position being probed. Fig. 2 shows the mean responses to each serial position. Each line on the Figure represents the responses produced to a given probe item, with the peaks representing correct responses. For example, the line with a peak at Response = 4 shows that when item 4 is presented at test, participants correctly identified it as having occurred in Position 4 about 48% of the time, misidentified as having occurred in Position 3 about 20% of the time, in Position 5 about 15% of the time, and so on.

Thus the peaks of the curves represent a standard serial position curve, and it is evident that the "signature" serial position curve expected by a temporal distinctiveness model such as SIMPLE (for single-item probe tasks of this type) was obtained, with extensive recency and smaller primacy being observed. Here as elsewhere in the paper, for the purposes of analysis we examined primacy and recency in two ways. First, we examined the mean slope of the serial position curve for the first three items (a measure of primacy) and the last four items (a measure of recency). Second, we examined mean performance for the same primacy (three) and recency (four) items. The impressions of greater primacy than recency were confirmed in a combined analysis of Experiments 1 and 2, which is reported after Experiment 2.

It is also evident that, again as normal, items that are not recalled as having appeared in their correct positions tend to be recalled as having occurred in nearby positions. These results replicate several previous studies. The resulting transposition error gradient is shown in the inset panel, which shows the number of positional errors as a function of positional distance. The straight line represents the proportion of errors that would have occurred by chance (there are more opportunities for short-distance errors than for long-distance errors).

Discussion

The primary aim of Experiment 1 was to provide memory data that could be compared with the timing identification data from Experiment 2 below, so discussion and interpretation of results is deferred.

Experiment 2

In Experiment 2 the absolute identification of temporal durations was examined. The durations were derived from the probed recall memory task, reported above. Specifically, the stimuli for the identification experiment were se-

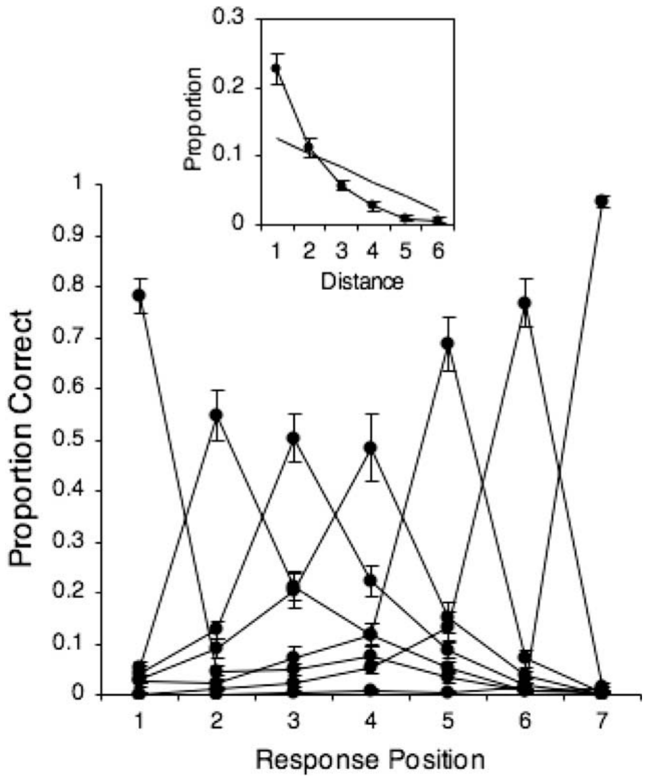

Fig. 2. Mean correct responses as a function of serial position in probed serial recall (Experiment 1).

ven tones differing only in their temporal durations, with the seven durations being the same as the temporal distances of items in memory (at the time retrieval was required) in Experiment 1. This allows a test of the hypothesis that similar serial position curves and error transposition gradients will be seen in the duration identification task as in the memory task.

Methods

Participants

The participants who completed Experiment 1 also completed Experiment 2.

Materials

The experiment was run on computer. The stimuli were 1000 Hz sinusoidal tones. The durations of each tone are presented in Table 1. There were seven tones in total, equally spaced on a linear scale such that each tone was 333 ms longer than the previous tone when arranged in ascending order of duration. The shortest tone was 333 ms and the longest tone was 2333 ms. Tones were labelled 1–7 in ascending order of duration.

Visual feedback was provided throughout the task on the visual display of the computer as the number of the correct test stimulus.

Procedure

Participants completed the experiment sitting in a quiet room at a comfortable distance from the computer. During each session, participants completed the absolute identification of duration task, plus a probed recall task, reported here as Experiment 1. Half the participants completed the probed recall task followed by the absolute identification of duration task and half the participants completed the tasks in reverse order.

Participants were told that they would hear some tones that differed in duration and that their task would be to identify the tones during a test phase, based on their duration. Participants were instructed that they would first hear seven tones in ascending order of duration, labelled such that Tone 1 was the shortest, and Tone 7 was the

Table 1
Durations of tones, and temporal distances of items in memory, for Experiments 1 through 6

Item number	Duration/distance (ms)			
	Expts 1 and 2	Expts 3 and 4 (short/immediate)	Expts 3 and 4 (long/delayed)	Expts 5 and 6
1	333	200	4200	250
2	666	400	4400	500
3	1000	600	4600	750
4	1333	800	4800	1500
5	1666	1000	5000	1750
6	2000	1200	5200	2000
7	2333	1400	5400	2750
8		1600	5600	3000
9		1800	5800	3250
10		2000	6000	

longest, and that this procedure would be repeated once. During this initial exposure phase of the experiment, participants were instructed to pay attention to the duration of each tone so that they would be able to identify each of the tones by their durations during the test phase. After each tone was presented, the participant was required to indicate which tone they had just heard by pressing specially labelled keys on a keyboard. Immediately following their response, the feedback display "That was Tone X" appeared in the middle of the computer screen for 1000 ms, indicating which tone had just been played. A further pause of 1000 ms followed, during which time the screen was blank, and the next tone was then presented. After each of the seven tones had been presented in ascending order twice through, there was a pause to allow the participant to ask any questions before starting the test phase of the experiment. Participants pressed the spacebar when they were ready to start the test phase.

During the test phase of the experiment, tones were presented in random order with the constraint that each tone be presented no more than 36 times in total. After each tone was presented, the participant was required to indicate as quickly as possible which tone they had just heard by pressing the specially labelled keys on the keyboard. Responses were recorded and timed by the computer. Immediately following their response, the feedback display "That was Tone X" appeared in the middle of the computer screen for 1000 ms. A further pause of 1000 ms followed, during which time the screen was blank, and the next tone was then presented. After 84 tones had been presented, participants were given the opportunity to pause briefly, and pressed the spacebar when they were ready to continue. Participants completed a total of 252 test trials before the task was complete.

Results

Fig. 3 shows the proportion of times each response was made to each tone duration. Each line represents a presented duration, with the horizontal axis representing the response given. Note that the shortest durations are represented in the right-hand side of the figure, to bring out the correspondence between short tone durations and the temporal distances of more recent items (Fig. 2). The inset panel shows that transposition error gradient.

Initial inspection of the graph reveals strong qualitative similarities between Figs. 2 and 3, with a strong recency effect corresponding to better performance both for recent items in Experiment 1, and for the corresponding temporal durations in Experiment 2. A combined analysis of Experiments 1 and 2 was carried out, and confirmed the similarities between the serial position curves. Analysis of mean performance for the first three (primacy) and last four (recency) items revealed that recency items were associated with better performance than primacy items: $F(1,15) = 33.01$, $MSE = 0.25$, $p = .0004$. However there was no main effect of Experiment (Experiment 1 vs. Experiment 2): $F(1,15) = 0.08$, $MSE = 0.002$, $p = .78$, and, crucially,

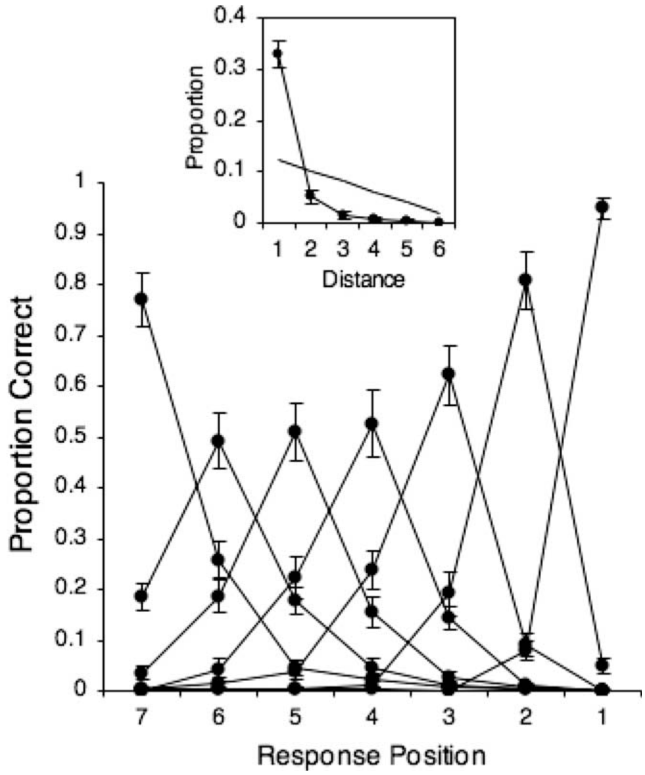

Fig. 3. Mean proportion of responses made to each tone duration in Experiment 2. "1" refers to the shortest duration; "7" to the longest.

no interaction between Experiment and the primacy/recency factor: $F(1,15) = 0.29$, $MSE = 0.002$, $p = .60$.

Analysis of slopes confirmed the similarities between Experiments 1 and 2. Absolute slopes were used to overcome the fact that recency slopes are positive and primacy slopes are negative. Absolute slopes did not vary as a function of experiment: $F(1,15) = 0.27$, $MSE = 0.001$, $p = .61$; and primacy and recency slopes did not differ from each other: $F(1,15) = 0.79$, $MSE = 0.003$, $p = .39$. Most importantly, the critical interaction between Experiment and primacy/recency was also not significant: $F(1,15) = 0.004$, $MSE = 0.00001$, $p = .95$.

Discussion

The aim of Experiments 1 and 2, taken together, was to examine the general hypothesis that retrieval of memories is akin to discrimination of temporal durations, where the temporal durations correspond to the temporal distances of memories at the time they must be retrieved. The data provided support for this conclusion: The recency in probed serial recall is paralleled by superior identification of relatively short temporal durations, and the smaller amount of primacy is paralleled by a small advantage for the longest temporal durations in the absolute identification task. Elvevåg, Brown, McCormack, Vousden, and Goldberg (2004), in a study of timing in patients with schizophrenia, found a similar result to that obtained here. The correspondence between the serial position curves is not perfect. However the results appear broadly consistent with the hypothesis that asymmetrical primacy and recency effects in the serial memory task can be understood by viewing memory retrieval as a temporal discrimination task.

Finally, we note that the serial position curve for absolute identification (with better performance on the shorter stimuli) would be expected to have turned out differently if different durations had been used. For example, Brown et al. (2005) found that shorter durations could be either better identified or worse identified, depending on the spacing of the stimulus durations. Thus it seems unlikely that the serial position curve reported here simply reflects the position of different durations in the sequence of stimuli; rather, the spacing of durations within the set is crucial, and a different serial position curve would be obtained if the durations had not corresponded to the temporal distances of items in the memory task.

Experiment 3

In Experiment 3 we extended the approach to immediate and delayed free recall. In free recall, participants are required to recall as many words as they can remember, in any order, from a list. The key explanandum that we focus on here is the reduction or abolition of recency with a filled delay (e.g. Glanzer & Cunitz, 1966), such that immediate free recall is typically characterised by large recency and small primacy, while delayed free recall is characterised by the absence of recency along with small primacy. Our focus here is on the abolition of the recency effect with the passage of time, as some or all of the primacy effect in free recall is typically assumed to reflect processes such as rehearsal (e.g. Tan & Ward, 2000).

According to temporal distinctiveness models, the abolition of recency with the passage of time in free recall tasks is due to the particular reduction in the temporal distinctiveness of late-list items (which also tend to be recalled first) as time passes (e.g. Bjork & Whitten, 1974; Brown, Della Sala, et al., 2007; Brown, Neath, et al., 2007; Crowder, 1976). According to the approach proposed in the present paper, it should be possible to understand the change in recency effects after a filled delay in terms of the changing relative discriminabilities of the temporal durations that correspond to the temporal distances in the past of list items in the immediate and delayed conditions. Thus the logic of Experiments 3 and 4 is the same as of Experiments 1 and 2 above: Experiment 3 looks at serial position effects in immediate and delayed free recall, and Experiment 4 uses an absolute identification task to assess the discriminability of tones differing only in temporal duration, where the temporal durations of the tones correspond to the temporal distances of items in Experiment 3.

In order to achieve reasonable levels of performance on the absolute identification task (Experiment 4), it was necessary to use relatively short (10-item) lists in the present free recall experiment. This is expected to lead to greater and more temporally extended primacy than is seen in free recall of longer lists. Also, we note at the outset that the comparison between memory and timing tasks cannot be perfect in this case, because (unlike in Experiment 1) there is no experimental control over the exact time at which list items are free recalled. For example, to the extent that early-presented items are recalled after late-presented items, their temporal discriminabilities at the time they are retrieved will be additionally reduced. We return to this issue in the discussion.

Methods

Participants

Nineteen participants (mean age 25 years) from the University of Warwick took part in the experiment. Each received payment for taking part in the experiment. Participants were randomly assigned to one of two conditions, which differed in terms of how long after list presentation they were asked to start to recall. Half the participants first completed the Immediate condition and then the Delay condition; the other half completed the conditions in the reverse order.

Materials

The experiment was run on computer and presentation of the stimuli was controlled by purpose written software. The stimuli were 280 four letter nouns, drawn from the MRC Oxford Psycholinguistic Database. Each word had a Kucera-Francis frequency between 20 and 683, and an imageability rating of between 234 and 670. All words were presented visually on the computer screen. Participants were presented with a total of 14 lists in each condition (immediate and delayed recall). Each list consisted of 10 words, and was constructed by drawing 10 words at random without replacement from the 280 words. This ensured that each participant never saw the same word twice throughout the whole experiment. No feedback was given during the experiment.

Procedure

All participants completed the Immediate and Delay condition of the experiment over two sessions held on different days. For logistical and economic reasons, the experiment was carried out in conjunction with another experiment. During each session, participants therefore completed either the Immediate or Delay condition of this experiment, in addition to an absolute identification of duration experiment, reported here as Experiment 6. The order in which participants completed each condition of the two experiments was counterbalanced so that an equal number of participants completed the conditions in each possible order.

Participants completed the experiment sitting in a quiet room at a comfortable distance from the computer. Participants were told that they would see a list of 10 words, appearing one at a time, on the computer screen, and that they would be asked to recall as many of the words as possible. Each word appeared in the middle of the screen for 170 ms, and in between presentation of each word the screen was blank for 30 ms. In the Delay condition, 230 ms after the last word had been presented, a randomly selected odd number appeared in the middle of the computer screen for 4000 ms. During this delay, participants were instructed to count aloud backwards by repeatedly subtracting 2 from the number they saw on the computer screen. The purpose of filling the delay with such a task was to prevent participants from rehearsing the presented words during the delay. After the delay, a cue (a ?) appeared in the middle of the screen, and the computer beeped. The participants were asked to stop counting and to verbally recall as many of the words presented in the most recent list as possible, in any order, when the cue appeared. A maximum of 30 s was allowed to recall the list; participants were however allowed to continue to the next trial after 15 s if they could not recall any more words from the current list. After seven trials there was a 2 min break and then the experiment continued. Participants completed a total of 14 trials before the task was complete. The procedure for the Immediate condition was the same, except the cue to recall the list appeared 230 ms after presentation of the last word in the list; otherwise the procedure was the same. The whole session was recorded on tape. The first two lists in each condition familiarized participants with the procedure and were not included in the analysis.

Results

For each list, the number of words correctly recalled was noted during the session and checked with reference to the tape recording as necessary. One concern, given the short lists, was the possibility of ceiling effects. Two participants scored close to ceiling on both primacy and recency items, and scored more than two standard deviations greater then the mean overall; data from these two participants were removed prior to analysis.

The serial position curves are shown in Fig. 4, and are typical for free recall of short lists when rehearsal is prevented. Larger recency is characteristically observed for longer lists than the ones used here, which contained just 10 items in order to preserve comparability with the parallel absolute identification experiment (reported next as Experiment 4). We report analyses of Experiments 3 and 4 separately, because Experiment 3 adopted a within-subjects design while Experiment 4 was between-subjects. ANOVA on mean levels of performance on the primacy (first three items) and recency (last four items) portions of the serial positive curve found an overall effect of condition (immediate vs. delayed): $F(1,16) = 202.8$, $MSE = 0.59$, $p < .001$. There was no overall effect of primacy vs. recency, $F(1,16) = 0.36$, $MSE = 0.01$, $p = .56$, but there was a marginally significant interaction between condition and primacy-recency: $F(1,16) = 3.16$, $MSE = 0.04$, $p = .09$, reflecting the expected greater recency than primacy for the immediate relative to the delayed condition. (Cleaner results can be obtained with a narrower definition of recency, but it was felt important to maintain a consistent approach across experiments and tasks.)

Analysis of the absolute slope values were also undertaken as for the previous experiments. Slopes were smaller in the delayed condition, $F(1,16) = 19.77$, $MSE = 0.13$, $p < .0001$, but did not differ overall between primacy and recency, $F(1,16) = 0.54$, $MSE = 0.005$, $p = .47$, and there was no interaction: $F(1,16) = 0.01$, $MSE = 0.000124$, $p = .91$.

Discussion

The purpose of Experiment 3 was to provide data that could be compared with data from an analogous temporal discrimination task (Experiment 4), so discussion is deferred until then. However we note that the relatively smooth serial position curves, with temporally extended primacy, are typical of free recall of short lists and indeed are predicted by temporal distinctiveness models. When longer lists must be recalled, it is common to see near perfect performance on the last presented item; here performance was only at about 75% for the last presented item, and the asymmetry between primacy and recency was smaller than is normally seen when longer list lengths are used. This difference is assumed to reflect the tendency for forward-ordered recall to occur, even in free recall tasks, when short and relatively rapidly presented lists are used (see Neath & Crowder, 1996). Recency items will lose some of their relative advantage when they are not the first items recalled, either because of the passage of time during recall, or due to output interference.

Experiment 4

In Experiment 4, performance on the absolute identification of two series of temporal durations was examined. Each temporal duration was set to be equal to the time that would have elapsed at the end of list presentation since each item was first presented in Experiment 3 above. One series of durations was based on the time that would have elapsed assuming immediate recall at the end of pre-

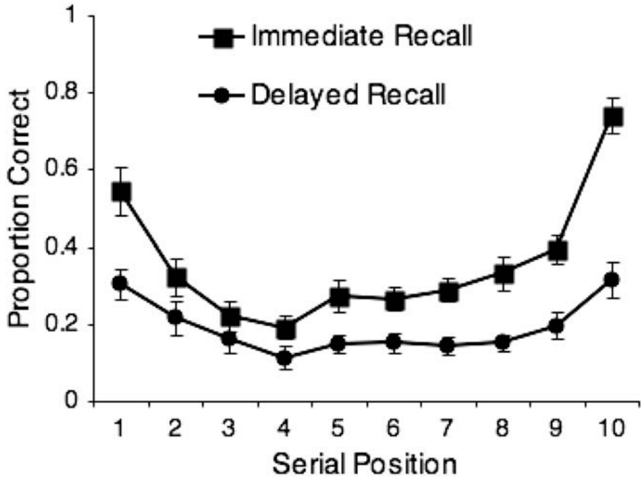

Fig. 4. Serial position curves for immediate and delayed free recall (Experiment 3).

sentation; the other was based on the time that would have elapsed assuming a retention interval at the end of presentation and prior to recall.

Methods

Participants

Thirty-two undergraduate students from the University of Warwick, with a mean age of 20 years, participated in return for course credit. They were randomly assigned to one of two conditions, which differed in terms of the lengths of the temporal durations in the series to be identified. Sixteen participants completed a Short condition and 16 completed a Long condition.

Materials

Presentation of the stimuli was controlled by purpose written software. The stimuli were 1000 Hz sinusoidal tones. All tones were presented over headphones, with adjustable volume control. The durations of each tone in the two conditions are given in Table 1. There were 10 tones in each condition, equally spaced on a linear scale such that each tone was 200 ms longer than the previous tone when arranged in ascending order of duration. The shortest tone in the Short condition was 200 ms and the longest tone was 2000 ms. Tones in the Long condition were created by increasing the duration of the tones in the Short condition by 4000 ms. Visual feedback was provided throughout the task on the visual display of the computer as the number of the correct test stimulus.

Procedure

Participants completed the experiment sitting in a quiet room at a comfortable distance from the computer. The procedure for both conditions was identical. Participants were told that they would hear some tones that differed in duration and that their task would be to identify the tones during a test phase, based on their duration. Participants were informed that they would first hear 10 tones in ascending order of duration, labelled such that Tone 1 was the shortest, and Tone 10 was the longest, and that this procedure would be repeated once. During this initial exposure phase of the experiment, participants were instructed to pay attention to the duration of each tone so that they would be able to identify each of the tones by their durations during the test phase. After each tone was presented, the participant was required to indicate which tone they had just heard by pressing the appropriate one of ten specially labelled keys on a keyboard. Immediately following their response, the feedback display "That was Tone X" appeared in the middle of the computer screen for 1000 ms, indicating which tone had just been played. A further pause of 1000 ms followed, during which time the screen was blank, and the next tone was then presented. After each of the 10 tones had been presented in ascending order twice through, there was a pause to allow the participant to ask any questions before starting the test phase of the experiment. Participants pressed the spacebar when they were ready to start the test phase.

During the test phase of the experiment, tones were presented in random order with the constraint that each tone be presented 12 times in total. After each tone was presented, the participant was required to indicate as quickly as possible which tone they had just heard by pressing the specially labelled keys on the keyboard. Responses were recorded and timed by the computer. Immediately following their response, the feedback display "That was Tone X" appeared in the middle of the computer screen for 1000 ms. A further pause of 1000 ms followed, during which time the screen was blank, and the next tone was then presented. After 40 tones had been presented, participants were given the opportunity to pause briefly, and pressed the spacebar when they were ready to continue. Participants completed 120 test trials before the task was complete.

Results

Fig. 5 shows the proportion of correct responses that was produced to durations at each serial position (the

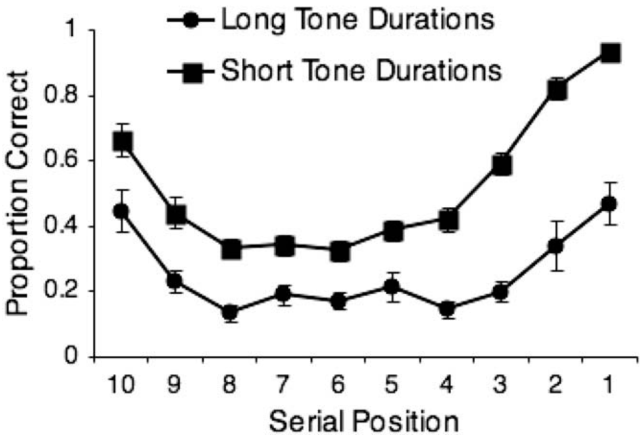

Fig. 5. Mean number of each responses made to each tone duration in Experiment 4.

shortest durations at the right-hand side of the figure, to facilitate comparison with Fig. 4). The predicted pattern is observed: For the "short" series the tones with the shortest temporal durations were most accurately identified; the mid-series tones were least accurately identified, and the longest tones were identified more accurately than the mid-series tones but were not as well identified as the short tones. For the "long" series, the relative advantage of the shortest tones largely disappeared. Indeed, somewhat paradoxically, the serial position curve obtained from the duration identification task appears rather more similar to a standard free recall curve than did the actual free recall data from Experiment 3.

ANOVA on mean levels of performance on the primacy (longest three items) and recency (shortest four items) portions of the serial position curve found an overall effect of experimental condition: $F(1,30) = 82.68$, $MSE = 1.49$, $p < .0001$. There was an effect of primacy vs. recency, $F(1,30) = 17.38$, $MSE = 0.21$, $p < .0001$, and there was a significant interaction between condition and primacy-recency: $F(1,30) = 12.48$, $MSE = 0.15$, $p = .002$, reflecting the expected greater recency than primacy for the durations corresponding to immediate free recall (shorter durations) relative to the durations corresponding to the delayed free recall condition (longer durations). Analysis of simple effects confirmed that recency was greater than primacy for the short durations: $t(15) = 7.09$, $p < .0001$, but that primacy and recency did not differ for the long durations: $t(15) = 0.37$, $p = .71$.

Analysis of the absolute slope values were also undertaken as for the previous experiments. Slopes did not differ between the two experimental conditions, $F(1,30) = 1.82$, $MSE = 0.02$, $p = .19$, did not differ overall between primacy and recency portions of the curve, $F(1,30) = 0.46$, $MSE = 0.005$, $p = .49$, and there was no interaction: $F(1,30) = 1.32$, $MSE = 0.013$, $p = .26$.

Discussion

The aim of Experiments 3 and 4 was to examine whether the recency in free recall, along with its abolition after a filled delay, could be understood in terms of the change in the discriminabilities of the temporal distances of items in the two conditions. Results were more mixed than those from the previous experiments, because the requirement to use short and rapidly presented lists of items in the memory task led to a serial position curve different from that seen with free recall of longer lists. As we noted at the outset, the case of free recall provides a less neat comparison than does probed serial recall (Experiment 1), because not every item can be recalled immediately after list presentation is complete, and hence the exact temporal distance of each item's original presentation at the time it is recalled will vary. For this reason, we return to the use of a probed task for the subsequent memory experiments.

Nonetheless, given the difficulties inherent in using a memory task where recall unfolds over time, the overall pattern of results appears broadly consistent with the hypothesis that memory is akin to temporal discrimination. In both immediate and delayed recall conditions, the items that were most likely to be recalled were those whose temporal distances at the time of retrieval were most easily discriminable in a separate absolute identification task. To provide a rough indication of association, the overall rank correlation between memory performance and correct identification of the corresponding temporal durations was .83 ($t(18) = 6.2$; $p < .0001$).

Experiment 5

Next, we returned to the use of a probed recall memory paradigm in order to examine serial position phenomena associated with grouping effects. Grouping effects are well established in serial recall tasks (e.g. Hitch et al., 1996; Ryan, 1969a; Ryan, 1969b) and reflect a tendency for (a) grouped lists to be better recalled, and (b) within-list serial position effects to occur, such that small primacy and recency effects are seen for each group within a list, as well as for the list as a whole. For example, if a six-item list is presented in two groups of three (A B C–D E F), item C might be recalled better than item B (recency at the level of the first group) and item D might be recalled better than item E (primacy at the level of the second group). Here we focus just on the within-list serial position effects, and we use a probed memory task rather than the forward serial recall task that is normally employed. Use of the probed memory task allows control over the temporal distances of items at the time they must be recalled, as in Experiment 1.

Explanations of grouping effects have typically used hierarchical representations of some kind, such that items' within-group positions and within-list positions are separately represented (e.g. Brown, Della Sala, et al., 2007; Brown, Neath, et al., 2007; Brown et al., 2000; Burgess & Hitch, 1992; Burgess & Hitch, 1999; Henson, 1998), and much debate concerns whether the within-group dimension is positional or temporal (e.g. Henson, 1999; Ng & Maybery, 2002, see Neath & Brown, 2006, for discussion). Here however our concern is simply with whether the group-level serial position effects might reflect the easier discriminabilities of the temporal distances of the end-group items. It is already well established that locally isolated items are more accurately identified in absolute identification tasks (Neath, Brown, McCormack, Chater, & Freeman, 2006) because they have fewer near neighbors with which they may be confused. In the memory case, the temporal distances of items at the starts and ends of groups are more isolated than are the temporal distances of mid-group items, because they have nearby items (with very similar temporal distances) only on one side. Thus the main purpose of the present experiment was to collect grouping data using a probed memory task in which the temporal distances of items at the time of recall were known, in order to compare with a parallel duration discrimination task (Experiment 6, below).

Methods

Participants

Twenty undergraduate students from the University of Warwick, with a mean age of 27 years, participated in the experiment and received payment for doing so.

Materials

The experiment was run on computer and presentation of the stimuli was controlled by purpose written software. The stimuli were nine non-confusable letters. The letters were presented auditorily via headphones. Each list consisted of nine letters, and was constructed by randomly shuffling the nine stimuli on each trial. Participants were presented with a total of 216 lists. The probe was played after list presentation via the headphones. Visual feedback was provided throughout in the form of the correct position of the probe stimulus.

Procedure

Participants completed the experiment sitting in a quiet room at a comfortable distance from the computer. Participants were told that they would hear a list of nine letters. Each letter played for 250 ms, and interspersed by a silent gap of 500 ms after the third and sixth letter. Thus after the ninth letter had been played, a total of 3250 ms had elapsed. After the last letter had been played the probe letter was played. This was the cue for participants to recall the presented position of the probe item. Participants were instructed to respond as soon as they could, by pressing specially labelled keys on the keyboard (each key corresponding to a serial position in the list). Responses were recorded and timed by the computer. Immediately following their response, the feedback display "That was position X" appeared in the middle of the computer screen for 1100 ms. After 36 trials there was an opportunity to take a short break and then the experiment continued. Participants completed a total of 216 trials before the task was complete. At the end of the task, each serial position had been probed 24 times.

Results

The first 36 trials (four for each serial position) familiarized participants with the procedure and were not included in the analysis, leaving a total of 20 probes per position for analysis. For each list, responses were recorded as a function of the serial position being probed. Fig. 6 shows the mean correct responses as a function of serial position. Two key effects are readily apparent. First, as is normal in probed serial recall tasks, there is extended recency across the entire list, along with a smaller amount of primacy. This replicates the signature prediction of a temporal distinctiveness model such as SIMPLE when testing is immediate upon list presentation. Second, there are clear within-group primacy and recency effects, as are seen when forward serial recall of grouped lists is required, although we note that such effects may have been attenuated for the final three serial positions due to near-ceiling effects. Further discussion of the results and formal analysis are deferred until after the results of the parallel duration identification task are reported.

Experiment 6

Experiment 6 examined absolute identification of tones, where the temporal durations of the tones corresponded to the temporal distances of items at the time they needed to be recalled in Experiment 5 above. As before, the purpose of the experiment was to examine whether similar serial position curves would be seen in the identification task as were seen in the memory task.

Methods

Participants

Nineteen undergraduate students from the University of Warwick participated in the experiment and received payment for doing so.

Materials

The experiment was run on computer and stimulus presentation was controlled by purpose written software. The stimuli were 1000 Hz sinusoidal tones. All tones were presented over headphones, with adjustable volume control. The durations of each tone are presented in Table 1, and corresponded to the temporal distances of memory items

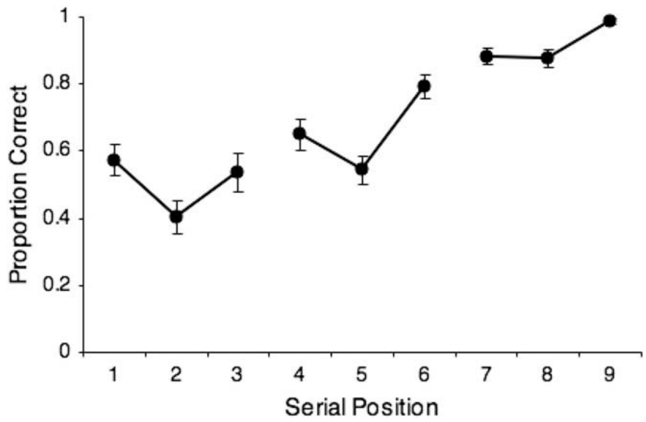

Fig. 6. Mean correct responses as a function of serial position in probed serial recall (Experiment 5).

in Experiment 5. There were nine tone durations, spaced such that difference in duration within groups was 250 ms and the difference was 750 ms between groups. The shortest tone was 250 ms and the longest tone was 3250 ms. Tones were labelled 1–9 in ascending order of duration. Visual feedback was provided throughout the task on the visual display of the computer by displaying the number of the correct test stimulus.

Procedure

Participants completed the experiment sitting in a quiet room at a comfortable distance from the computer. During each session, participants completed the absolute identification of duration task, in addition to an unrelated free recall memory task. Participants were told that they would hear some tones that differed in duration and that their task would be to identify the tones during a test phase, based on their duration. Participants were instructed that they would first hear nine tones in ascending order of duration, labelled such that Tone 1 was the shortest, and Tone 9 was the longest, and that this procedure would be repeated once. During this initial exposure phase of the experiment, participants were instructed to pay attention to the duration of each tone so that they would be able to identify each of the tones by their durations during the test phase. After each tone was presented, the participant was required to indicate which tone they had just heard by pressing specially labelled keys on a keyboard. Immediately following their response, the feedback display "That was Tone X" appeared in the middle of the computer screen for 1000 ms, indicating which tone had just been played. A further pause of 1000 ms followed, during which time the screen was blank, and the next tone was then presented. After each of the nine tones had been presented in ascending order twice through, there was a pause to allow the participant to ask any questions before starting the test phase of the experiment. Participants pressed the spacebar when they were ready to start the test phase.

During the test phase of the experiment, tones were presented in random order with the constraint that each tone be presented no more than 32 times in total. After each tone was presented, the participant was required to indicate as quickly as possible which tone they had just heard by pressing the specially labelled keys on the keyboard. Responses were recorded and timed by the computer. Immediately following their response, the feedback display "That was Tone X" appeared in the middle of the computer screen for 1000 ms. A further pause of 1000 ms followed, during which time the screen was blank, and the next tone was then presented. After 48 tones had been presented, participants were given the opportunity to pause briefly, and pressed the spacebar when they were ready to continue. Participants completed a total of 288 test trials before the task was complete.

Results

Fig. 7 shows the proportion of correct responses that was produced to durations at each serial position (the shortest durations at the right-hand side of the figure, to facilitate comparison with Fig. 6). It is evident that the expected pattern was obtained: Short temporal durations were better identified overall, and the durations corresponding to end-group items were better identified.

Discussion

The overall pattern of findings, represented by the qualitative similarity between Figs. 6 and 7, appears consistent with the general hypothesis that memory retrieval involves the discrimination of items in terms of their location along a temporal distance dimension. More specifically, the group-level primacy and recency effects observed in probed recall of a grouped list (Experiment 5) are mirrored in the temporal discrimination task (Experiment 6).

Formal analyses examined the similarity of the key effects between experiments. ANOVAs used experiment (Experiment 5 vs. Experiment 6) as a between-subjects factor, and Group (with three levels) and within-group position (also with three levels) as within-subjects factors. There were main effects of experiment, $F(1,37) = 4.85$, $MSE = 0.77$, $p = .03$, group, $F(2,74) = 171.36$, $MSE = 3.74$, $p < .0001$, and within-group position, $F(2,74) = 81.77$, $MSE = 0.94$, $p < .0001$. There were two significant interac-

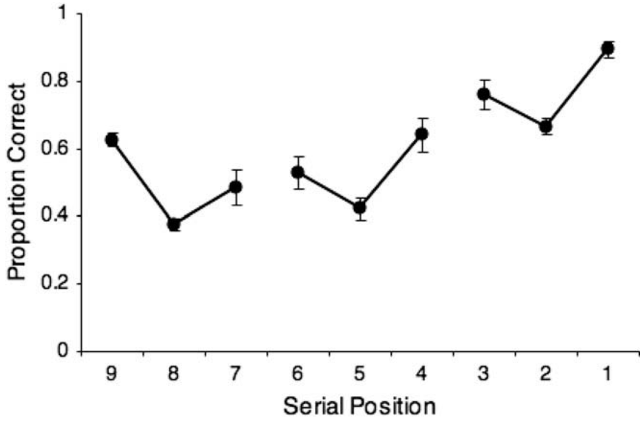

Fig. 7. Proportion of correct responses that was produced to durations at each serial position (Experiment 6).

tions. The first was between experiment and group, $F(2,74) = 7.49$, $MSE = 0.16$, $p = .001$, reflecting greater overall recency in Experiment 5 than in Experiment 6, and the second was between group and within-group position, $F(2,74) = 81.77$, $MSE = 0.94$, $p < .0001$, reflecting smaller within-group effects for later groups. Post-hoc analyses revealed effects of both group and within-group position for both the memory and the timing task, and that end-group items were better remembered than mid-group items in all groups (all p's < .05).

In summary, the key effects of (a) large recency and small primacy and (b) grouping effects were clearly seen in both the memory task and the parallel duration identification task. Notwithstanding the quantitative differences between the results of Experiments 5 and 6, we take these results to be broadly consistent with the general hypothesis that memory retrieval is in important respects like temporal discrimination.

Despite the similarities between Figs. 6 and 7, it is important not to overstate the conclusions that can be drawn. First, there is clearly more to memory retrieval than temporal discrimination; we return to this in General discussion below. Second, in the context of grouping effects particularly, we make no claim that discriminability along a single temporal distance dimension is all there is to grouping. In particular, the ubiquity of transposition errors that preserve within-group position (e.g. items 3 and 6 exchanging), as noted by Ryan (1969a),Ryan (1969b) and others, strongly implicates some kind of underlying hierarchical representation that is not captured in the unidimensional temporal distance approach described here. Nonetheless, the results appear consistent with the suggestion that the group-level serial position effects may at least in part reflect the temporal discriminability of the items occupying end-group positions.

General discussion

The overall aim of the experiments reported above was to examine whether serial position effects in memory tasks could be understood in terms of the temporal distinctiveness of items in memory. What reason is there to believe in such a strong link between time and memory retrieval? In general terms, time has always been central to conceptions of episodic memory. Tulving (1983) viewed episodic memory as a system for storing temporally dated episodes or events and relations between such events (see also McCormack & Hoerl, 1999; Wheeler, Stuss, & Tulving, 1997). More specifically, several considerations motivate the idea that memories are organised along a temporal dimension as well as other dimensions (see Brown & Chater, 2001, and Brown & McCormack, 2006, for reviews). Animal timing, memory, and sequential behavior may have common roots in simple animal navigation and foraging behavior (e.g. Bateson & Kacelnik, 1997; Brown & Vousden, 1998; Gallistel, 1990). From an adaptive perspective timing and memory mechanisms could be related because the time elapsed since a memory was laid down can be used to predict probability of retrieval of that memory being necessary (e.g. Anderson & Milson, 1989; Anderson & Schooler, 1991; Schooler & Anderson, 1997). These and other functional and adaptive considerations have been reflected in both recent and older models of human memory, several of which have assigned a central role to time in explaining empirical phenomena such as recency effects. Some small-scale studies have found suggestive correlations between duration identification tasks and memory span performance (e.g. Elvevåg et al., 2004), while others have not (e.g. Elvevåg et al., 2003), but there has been little in the way of systematic investigation using a correlational approach.

An alternative approach is taken by Farrell and McLaughlin (2007), who found that serial recognition of items that were irregularly spaced in time during presentation was not affected by the temporal proximity of items, although temporal information was encoded as evidenced by participants' ability to perform a temporal recognition task. Along with other results (e.g. Lewandowsky et al., 2008) these findings appear consistent with the claim that an ordinal rather than (or in addition to) a temporal dimension may be involved in some varieties of short-term memory for serial order (see also Farrell, 2008). In addition, we note that the present paper more strongly justifies the relatively weak claim that the same mechanism *type* is involved in retrieval and temporal discrimination, rather than the stronger claim that the same mechanism *token* is involved.

Here we focussed on temporal distinctiveness models of memory in particular. Such models (e.g. Brown, Neath, et al., 2007) suggest that when the temporal distance of an item is less confusable with the temporal distances of other items, that item will be better recalled. We found evidence broadly consistent with this idea: In three pairs of experiments, involving probed serial recall of seven-item lists, free recall of 10-item lists, and probed recall of nine-item grouped lists, it was found that the serial position curve in a memory task was at least approximately paralleled by the serial position curve obtained when durations were required to be identified in a separate absolute identification task. The similarities were clearest in the probed serial recall memory tasks and their temporal parallels, with the largest discrepancies occurring for free recall. This pattern of results may well reflect the fact that time is passing as successive items are recalled, leading to a changing temporal perspective on the list along with the involvement of additional factors such as output interference. We take the results as broadly consistent with the claim, made by recent temporal distinctiveness models of memory, that memory retrieval requires temporal discrimination. It is at least unclear whether any other theoretical perspective could have predicted the similarities a priori.

It is important to note what we are not claiming. First, there is clearly more to memory retrieval than temporal discrimination; items are represented in memory along many other dimensions and hence factors other than discriminability along the temporal distance dimension will certainly influence memory (see Brown, Neath, et al., 2007, for the idea that the temporal distance is just one of many). Nonetheless, in tasks such as the ones used in the present paper where there is no systematic relation between the to-be-remembered items, and where strong recency (a signature of temporal distinctiveness models) is observed, it is likely the temporal dimension will be central. Second, as noted earlier, at least in forward serial recall tasks it is clear that a positional dimension as well as (or instead of) a temporal dimension is often important, with the balance between dimensions depending on task requirements (e.g. Lewandowsky et al., 2008). Such considerations would appear to act against the possibility of finding systematic relations between temporal discrimination performance and serial position curves in memory. However, despite these limitations, we observed strong qualitative similarities, although not a perfect correspondence, between serial position effects in a memory task and a separate timing task. We interpret these results as consistent with the suggestion that memory retrieval is, at least in part, akin to temporal discrimination.

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